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## On the nature of sub-millimetre galaxies

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**Abstract.** I discuss our current understanding of the nature of high-redshift ( $z > 2$ ) (sub)-millimetre-selected galaxies, with a particular focus on whether their properties are representative of, or dramatically different from those displayed by the general star-forming galaxy population at these epochs. As a specific case study, I present some new results on the one sub-millimetre galaxy which happens to lie within the Hubble Ultra Deep Field and thus benefits from the very best available ultra-deep optical-infrared *Hubble Space Telescope* and *Spitzer Space Telescope* imaging. I then consider what these and other recent results from optical-infrared studies of sub-millimetre and millimetre selected galaxies imply about their typical masses, sizes and specific star-formation rates, and how these compare with those of other star-forming galaxies selected at similar redshifts. I conclude with a brief discussion of the continued importance and promise of SCUBA2 in the era of *Herschel*.

### 1. Introduction

In recent years two alternative views of the high-redshift (sub)-millimetre selected galaxy population have emerged. Some authors have argued that the galaxies uncovered via the deep SCUBA, MAMBO, AzTEC and LABOCA sub-millimetre and millimetre wavelength surveys are basically high-redshift versions of the Ultra-Luminous Infrared Galaxies (ULIRGS) found in the local universe. In this picture they are thus galaxies of moderate stellar mass ( $< 10^{11} M_{\odot}$ ) involved in major mergers which produce a compact, short-lived starburst with a correspondingly extreme specific star-formation rate (SSFR=star-formation rate/galaxy stellar mass) (e.g. Gonzalez et al. 2011; Hainline et al. 2011; Engel et al. 2010). In contrast, others have argued (in some cases from the same primary data) that the evidence indicates that sub-millimetre galaxies simply represent the top end of the normal star-forming galaxy population at  $z = 2 - 3$ . In this scenario they are galaxies of high stellar mass ( $\approx 1 - 4 \times 10^{11} M_{\odot}$ ), which still have sufficiently large reserves or supplies of cool gas to produce very high levels of star formation, but in which this star formation is spatially-extended and is of a magnitude which is (at least on average) as “expected” given their large stellar masses and the typical SSFR at this epoch (e.g. Davé et al. 2010, Targett et al. 2011; Rujopakam et al. 2011).

The concept of a typical SSFR at  $z > 2$  is a fairly new one, and comes from recent (still somewhat controversial) studies of the so called “main sequence” of star-forming galaxies which indicate that the actively star-forming galaxy population displays a characteristic SSFR (over a reasonably large range of mass) which rises monotonically from  $z \approx 0$  to  $z \approx 2$  and appears to plateau at higher redshifts around a value of SSFR =

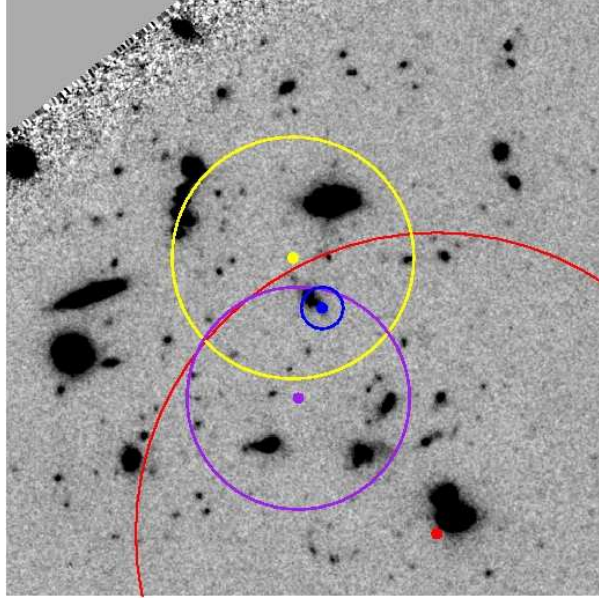


Figure 1. The positions and appropriate counterpart search radii of the 3 alternative detections of the sub-millimetre/millimetre galaxy in the Hubble Ultra Deep Field (HUDF) are shown superimposed on a greyscale of the appropriate sub-region of the *HST* WFC3/IR  $H_{160}$  image of the HUDF. The position/search radius of the BLAST  $250\mu\text{m}$  detection is indicated in red, the LABOCA  $870\mu\text{m}$  detection in purple, and the AzTEC  $1.1\text{ mm}$  detection in yellow. Within the intersection of the three counterpart search areas lies a single marginally-detected  $1.4\text{ GHz}$  radio source which ties the object to a galaxy which is clearly detected in the  $H_{160}$  image, despite being almost undetected in the ACS  $B$ -band image.

$2 \pm 2\text{ Gyr}^{-1}$  (Noeske et al. 2007; Daddi et al. 2007; Stark et al. 2009; Gonzalez et al. 2010). This characteristic SSFR displayed by ultraviolet-selected and mid-infrared selected star-forming galaxies at  $z > 2$  at least provides a helpful benchmark against which to judge whether or not sub-millimetre galaxies are genuinely pathological outliers from the general star-forming population in this epoch of maximum star-formation activity.

In this paper I briefly describe some of the latest observational evidence of relevance to this debate, focussing first on some new results on the one sub-millimetre galaxy which happens to lie within the ultra-deep optical (ACS) and near-infrared (WFC3/IR) imaging delivered by the *Hubble Space Telescope* (*HST*) in the Hubble Ultra Deep Field (HUDF). This case study illustrates rather clearly the challenge we continue to face in gaining a complete and robust understanding of high-redshift sub-millimetre galaxies. To properly establish their bolometric luminosities, temperatures, star-formation rates, gas/dust masses, stellar masses, pre-existing stellar populations, sizes and morphologies, requires the careful combination of the deepest available data spanning the wavelength range  $\lambda \simeq 4000\text{ \AA} \rightarrow 20\text{ cm}$  which, with current facilities, means handling multi-frequency datasets which vary by a factor of up to  $\simeq 500$  in angular resolution.

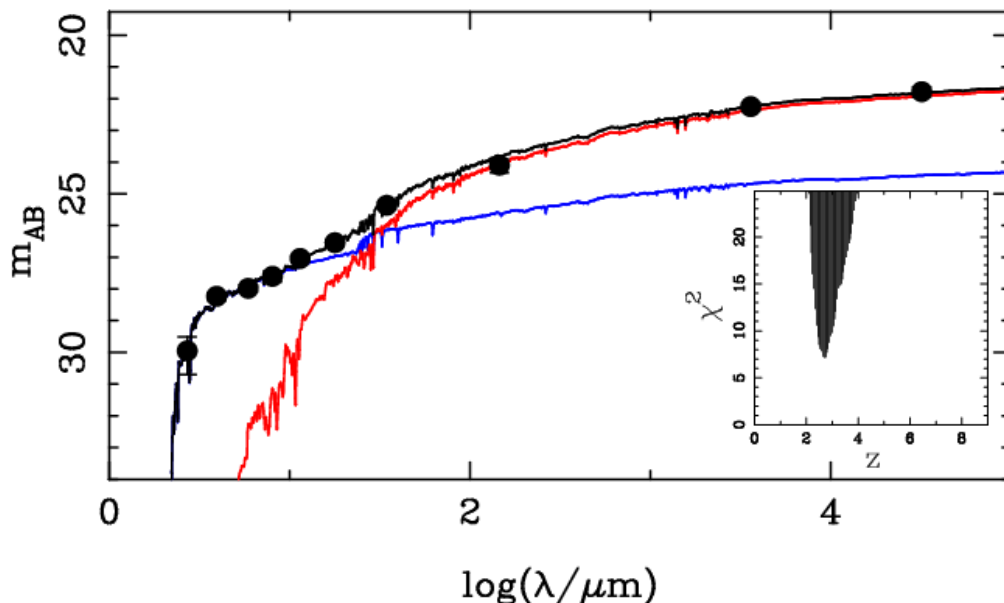


Figure 2. The best-fitting two-component SED fit to the *HST*-ACS + *HST*-WFC3/IR + *Spitzer*-IRAC photometry of the galaxy associated with the sub-millimetre source in the HUDF. The  $\chi^2$  inset shows that the only acceptable solution is a galaxy with an accurate and robust photometric redshift  $z = 2.97 \pm 0.09$ . The blue line indicates the contribution of the younger star-forming component to the overall SED fit (shown in black), while the red line indicates the contribution of the mass-dominant more mature stellar population. The inferred stellar mass is  $M_* \simeq 2.5 \times 10^{11} M_\odot$ , with uncertainties dominated by the modelling choices as discussed in the text.

## 2. A luminous sub-millimetre galaxy in the Hubble Ultra Deep Field

Surveys of the GOODS-South field at  $870 \mu\text{m}$  with the sub-millimetre camera LABOCA (Weiss et al. 2009), at  $1.1 \text{ mm}$  with the millimetre-wavelength camera AzTEC (Scott et al. 2010), and at  $250\text{--}500 \mu\text{m}$  with the BLAST far-infrared imager (Devlin et al. 2009; Dunlop et al. 2010) have each detected one source which lies with the region of the HUDF recently imaged to unprecedented depth at near-infrared wavelengths with Wide Field Camera 3 (WFC3) on the *HST* (e.g. McLure et al. 2010; Bouwens et al. 2010). Despite the large beams, the three independent positions delivered by these millimetre–far-infrared facilities, combined with ultra-deep VLA imaging at  $1.4 \text{ GHz}$ , have enabled the identification of a unique optical/infrared galaxy counterpart associated with the far-infrared dust emission, as shown in Figure 1. This galaxy is optically very faint ( $B \simeq 30 \text{ AB mag}$ ), but also extremely red, and its location in the sub-region of the HUDF imaged by WFC3/IR provides a unique opportunity to study an “ordinary”, unlensed sub-mm galaxy with *extra-ordinary* optical/infrared/mid-infrared imaging. As shown in Figure 2, the unparalleled 12-band optical-infrared photometry delivers an extremely robust and accurate photometric redshift of  $z = 2.97 \pm 0.09$ .

### 3. Stellar masses

The stellar mass of this HUDF galaxy as derived from the two-component spectral-energy distribution (SED) fit shown in Figure 2 is  $M_* \simeq 2.5 \times 10^{11} M_\odot$ . This value is derived using the evolutionary synthesis models of Bruzual & Charlot (2003), and assuming the initial mass function (IMF) of Chabrier (2003). As has been well documented in the literature, the choice of evolutionary synthesis model, IMF, and also adopted star-formation history all have systematic effects on estimated galaxy stellar masses, and so it is important to quantify the impact of such choices on derived stellar masses, and to assess the evidence for or against the various alternatives.

The first potential cause of significant uncertainty in derived stellar masses is redshift accuracy, and it is undoubtedly the case that the *random* errors in stellar masses are in effect often dominated by uncertainty in estimated redshifts. Such uncertainty is obviously ideally removed via a spectroscopic redshift but, in the case of the HUDF galaxy considered here, such spectroscopy is both impractical but also not really necessary, as the quality of the photometry yields such an unambiguous and accurate photometric redshift. Given high-quality photometry and a solid redshift, the uncertainty in stellar mass is undoubtedly dominated by choices made in the model-fitting process.

The first key modelling issue is the choice of star-formation history (SFH). The degree to which this is truly a free choice of course depends to some extent on the quality of the photometry. In an attempt to account for this uncertainty, Hainline et al. (2011) explored the use of two alternative single-component SFHs, adopting either an instantaneous starburst or a continuous star-formation history. Hainline et al. (2011) then averaged the two resulting estimates to produce the adopted stellar mass for each galaxy. In contrast, other authors (e.g. Michalowski et al. 2010) have assumed a two-component SFH, while others have attempted to go further and fit several independent components (e.g. Dye et al. 2008).

The assumption of a multi-component SFH generally leads to higher mass-to-light ratios and, in turn, higher stellar masses than the use of a single-component model. This is because while the starburst component can account for the ultraviolet (UV) emission (and the far-infrared emission from the UV-heated dust), the second (older) component is then free to contribute more stars with higher mass-to-light ratios (see also Schael et al. 2011). By contrast, the use of a single instantaneous starburst model limits the age of the *entire* stellar population to the young age of the starburst required to match the UV emission (and thus the true stellar masses are inevitably under-estimated), while in the continuous star-formation model the current star-formation rate is set by the UV emission and the total age is then limited in order not to overshoot the optical and the near-infrared part of the spectrum (assuming the galaxy has always formed stars at the same high rate). Indeed, Schael et al. (2011) have found that the stellar masses of the SHADES sub-millimetre galaxies (Coppin et al. 2006) derived using a two-component SFH are on average a factor of  $\simeq 2$  higher than when derived with a one-component SFH.

In the case of the HUDF sub-millimetre galaxy shown here in Figure 2, the situation is relatively straightforward because the optical-infrared data are of sufficient quality to demand a two-component fit (but do not require anything more complex). This object thus provides some further support for the general adoption of two-component fitting when modelling the optical–mid-infrared SEDs of sub-millimetre galaxies, thus favouring higher stellar masses compared to those derived on the assumption of single-component star-formation histories.

The second key modelling issue is the choice of stellar population evolutionary synthesis model. Here the new HUDF sub-millimetre galaxy can provide little guidance, as satisfactory fits can be achieved with a variety of spectral synthesis models. However, the key issue for the derivation of stellar masses centres on whether to adopt models which have a strong contribution from thermally pulsating asymptotic giant branch (TP-AGB) stars (as exemplified by the models of Maraston 2005), or models in which this phase of stellar evolution makes a relatively unimportant contribution to the integrated light from a galaxy’s stellar population (as is the case in the models of Bruzual & Charlot 2003). Hainline et al. (2011) explored both alternatives, and found that the stellar masses derived using the Bruzual & Charlot (2003) models were on average  $\approx 50\%$  higher than those calculated using the Maraston (2005) models.

While studies of sub-millimetre galaxies may not be able to directly resolve this issue, several other recent studies of other classes of galaxy indicate that the impact of the TP-AGB stars on integrated galaxy light is not nearly as strong as produced by the Maraston (2005) models. In particular, Kriek et al. (2010) have found that the average spectral energy distribution of post-starburst galaxies at  $0.7 < z < 2.0$  does not appear to display the excess near-infrared contribution predicted from the TP-AGB contribution in the Maraston models, and that the Bruzual & Charlot (2003) model provides a much better description of the data, even at the age ( $\approx 1$  Gyr) when the TP-AGB contribution should be near maximum (see also Conroy & Gunn 2010). For now, therefore, we favour the use of Bruzual & Charlot (2003) models over the Maraston (2005) models for the estimation of stellar masses.

The third analysis choice of importance for stellar mass calculation concerns the adopted stellar IMF. The choice clearly matters because the adoption of a Salpeter (1955) IMF yields stellar masses a factor of 1.8 higher than result from the adoption of the IMF favoured by Chabrier (2003). In general, the discussion of the IMF in the context of sub-millimetre galaxies has until recently focussed on whether a top-heavy IMF is required to reproduce the sub-millimetre number counts from current models of galaxy evolution (e.g. Baugh et al. 2005; Fontanot et al. 2007; Hayward et al. 2011). However, recently van Dokkum & Conroy (2010) have reported that the IMF in local ellipticals (the likely descendants of sub-millimetre galaxies) is, if anything, slightly steeper (bottom-heavy) than even the Salpeter (1955) IMF (see also Thomson & Chary 2011). Given this controversy, and since there is as yet no clear evidence that the IMF of sub-millimetre galaxies is systematically different from that of other galaxies, it makes sense to adopt the Chabrier (2003) IMF. This IMF was derived for the Milky Way and can be viewed as a conservative/neutral choice, in effect representing the middle ground between the top-heavy IMFs proposed by, for example, Baugh et al. (2005), and the bottom-heavy IMFs of Salpeter (1955) or van Dokkum & Conroy (2010). I also note that this “Chabrier IMF” is essentially identical to the “Canonical IMF” recently summarized by Weidner, Kroupa & Pflamm-Altenburg (2011). While I would argue that this IMF is the natural choice on the basis of current evidence, it must still be accepted that we have to live with a fundamental uncertainty of  $\sim \times 2$  in stellar masses until the uncertainty in the IMF in sub-millimetre galaxies is resolved. However, it is also important to note that the derived specific star-formation rate (SSFR) is, to first order, unaffected by this IMF uncertainty (it is of course possible that the observed starburst and the pre-existing mass-dominant stellar population have different IMFs), making it a particularly useful quantity for comparing the properties of different types of star-forming galaxies, as discussed further below.

In conclusion, the above discussion hopefully clarifies why our current preferred best estimate of the stellar mass of the sub-millimetre galaxy in the HUDF is based on a two-component SED fit, using Bruzual & Charlot (2003) models, and assuming a Chabrier (2003) IMF. The resulting fairly large stellar mass of  $M_* \simeq 2.5 \times 10^{11} M_\odot$  is consistent with the results reported by Schael et al. (2011) and Michalowski et al. (2010). Such values are substantially larger than the typical stellar masses of  $M_* \simeq 5 - 7 \times 10^{10} M_\odot$  reported by Hainline et al. (2011). However, they are not as extreme as some of the very large masses reported by Dye et al. (2008) using multi-component fitting and a Salpeter (1955) IMF.

#### 4. Dynamical and gas masses

We do not currently possess any CO spectroscopy of the sub-millimetre galaxy in the HUDF, but such data have now been gathered and analysed for a number of sub-millimetre galaxies, providing vital information on both the dynamical and molecular  $H_2$  gas masses in these objects (e.g. Tacconi et al. 2006; 2008). Such measurements can be used to provide a consistency test of the stellar mass estimates, and to infer the evolutionary state of the galaxy. Specifically, assuming that the extent of the CO line-emitting gas is the same as the extent of the stellar component, the sum of the gas and stellar masses should, within the uncertainties, be no larger than the dynamical mass. Using this approach, Engel et al. (2010) concluded that the stellar masses of the sub-millimetre galaxies derived by Michalowski et al. (2010) ( $\simeq 2 - 3 \times 10^{11} M_\odot$  after correction to the Chabrier (2003) IMF) are inconsistent with their gas and dynamical masses ( $M_{\text{dyn}} \simeq 3 \pm 1 \times 10^{11} M_\odot$ ; see also Tacconi et al. 2008). However, not only does this result appear to be statistically insignificant, but on the contrary it appears that new observations of CO 1-0 line emission mean that this test now in fact appears to provide further support for large stellar masses  $M_* > 10^{11} M_\odot$ .

Like most previous CO line observations of high-redshift sub-millimetre galaxies, Engel et al. (2010) detected the high-excitation lines (CO J=7-6, 6-5, 4-3 and 3-2), which trace denser and hotter gas, arguably likely confined to the central regions of a galaxy. Therefore, the derived dynamical masses may refer to regions smaller than the extent of the stellar component, so it is difficult to compare them directly with the stellar masses, given that the starlight typically has a half-light radius of  $r_{0.5} \simeq 3 - 4$  kpc (see below). Indeed, based on new VLA studies of low excitation CO(1-0) lines, Ivison et al. (2011) have found dynamical masses higher by a factor  $\simeq 2.4 - 4.1$  for two out of the three sub-millimetre galaxies for which Engel et al. (2010) have claimed inconsistencies between stellar and dynamical masses (HDF 76 and N2 850.2; the third one was not observed by Ivison et al. 2011). It is also worth noting that the mean value of  $M_{\text{dyn}}$  reported by Engel et al. (2010) is lower by a factor of  $\simeq 1.7$  (close to the magnitude of the claimed inconsistency in the stellar masses of Michalowski et al. 2010) than that typically derived from near-infrared integral-field spectroscopy of sub-millimetre galaxies ( $M_{\text{dyn}} \simeq 5 \pm 3 \times 10^{11} M_\odot$ ; Swinbank et al. 2006), although both values are formally consistent.

Adopting the CO(1-0) derived masses where available, and multiplying masses based on higher-frequency CO transitions by a factor of 2 (as inferred from Ivison et al. 2011), we find that the average value of the ratio  $(M_* + M_{\text{gas}})/M_{\text{dyn}}$  is  $1.18 \pm 0.30$ , adopting the stellar masses of Michalowski et al. (2010) after correcting to the Chabrier (2003) IMF. We conclude that the latest estimates of (sub)-millimetre dynamical masses

are in good accord with their stellar masses, and certainly cannot be used to rule out the higher values as inferred here from the adoption of two-component modelling and the Bruzual & Charlot (2003) models. However they do provide some tentative evidence against adoption of the Salpeter (1955) IMF which would push the inferred stellar masses of several (sub)-millimetre galaxies beyond the typical CO(1-0) inferred dynamical mass of  $M_{\text{dyn}} \approx 5 \times 10^{11} M_{\odot}$ .

Calculation of molecular ( $H_2$ ) gas masses in sub-millimetre galaxies is currently somewhat controversial due to uncertainty over what is the appropriate correction factor to apply when converting CO luminosities into total molecular gas masses. Here I simply note that given dynamical masses  $M_{\text{dyn}} \approx 5 \times 10^{11} M_{\odot}$  and typical stellar masses  $M_* \approx 3 \times 10^{11} M_{\odot}$ , current data would appear to allow molecular gas masses up to levels comparable with the stellar masses, which in fact would then allow CO luminosity to gas-mass conversion ratios possibly as large as the Milky Way value of  $M_{\text{gas}}/L'_{\text{CO}} = \alpha_{\text{CO}} = 4.5 M_{\odot} (\text{K km s}^{-1} \text{ pc}^2)^{-1}$ , or certainly  $\alpha_{\text{CO}} = 3.2\text{--}3.6 M_{\odot} (\text{K km s}^{-1} \text{ pc}^2)^{-1}$  (comparable to the conversion factor implied for nearby disc galaxies; Tacconi et al. 2010), rather than necessarily requiring  $\alpha_{\text{CO}} \approx 0.8 M_{\odot} (\text{K km s}^{-1} \text{ pc}^2)^{-1}$  as commonly adopted for ULIRGS (e.g. Downes & Solomon 1998; Tacconi et al. 2006; Daddi et al. 2010).

## 5. Sizes and morphologies

Because of the exquisite depth and high angular resolution of the WFC3/IR imaging, it is possible to determine rather accurately the rest-frame ( $B$ -band) optical morphology of the (sub)-millimetre galaxy in the HUDF. As illustrated in Figure 3 (bottom row of panels) the result of fitting a two-dimensional axi-symmetric model with variable Sérsic index, is that the galaxy is a disc ( $n = 1.09$ ) with a reasonably large half-light radius  $r_{0.5} \approx 4 \text{ kpc}$ . These parameter values are similar to the (albeit more uncertain) values derived using ground-based near-infrared imaging of  $\approx 15$  sub-millimetre galaxies by Targett et al. (2011), who reported median values of  $n = 1.08$  and  $r_{0.5} = 3.1 \text{ kpc}$ . Similar sub-millimetre galaxy rest-frame optical scalelengths have also been reported from *HST* NICMOS imaging by Swinbank et al. (2010). This case-study thus further strengthens the conclusion that typical sub-millimetre selected galaxies are massive star-forming disc galaxies at  $z \approx 2 - 3$ .

To explore the reliability of this result, we have also analysed the HUDF imaging of a low-redshift ( $z = 0.345$ ) disc/spiral galaxy, first from the ACS imaging at its actual redshift (Figure 3, top row) and second after artificially shifting it to  $z = 3$ , convolving it with the WFC3/IR  $H_{160}$ -band point-spread function, and planting the synthesized high-redshift spiral into the WFC3/IR  $H_{160}$  image (Figure 3, middle row). For a single object, the results can of course only be regarded as illustrative, but nonetheless are worthy of comment. First, the modelling of the actual ACS optical imaging delivers a best-fit model of a disc galaxy with  $r_{0.5} = 8 \text{ kpc}$ , and the expected spiral arm residual. Second, when the synthesized  $z = 3$  near-infrared image of the same galaxy is analysed, the model fitting returns identical parameters to within an accuracy of  $\approx 5\%$ , providing reassurance that, with near-infrared imaging of this quality and depth, the best-fitting parameters for the HUDF (sub)-millimetre galaxy can certainly be regarded as robust. Third, the residual image from the modelling of the redshifted spiral is dominated by a single, off-centre clump. This is exactly the sort of feature that might naively be interpreted as evidence for an interaction/merger, but in fact it can be seen that this is

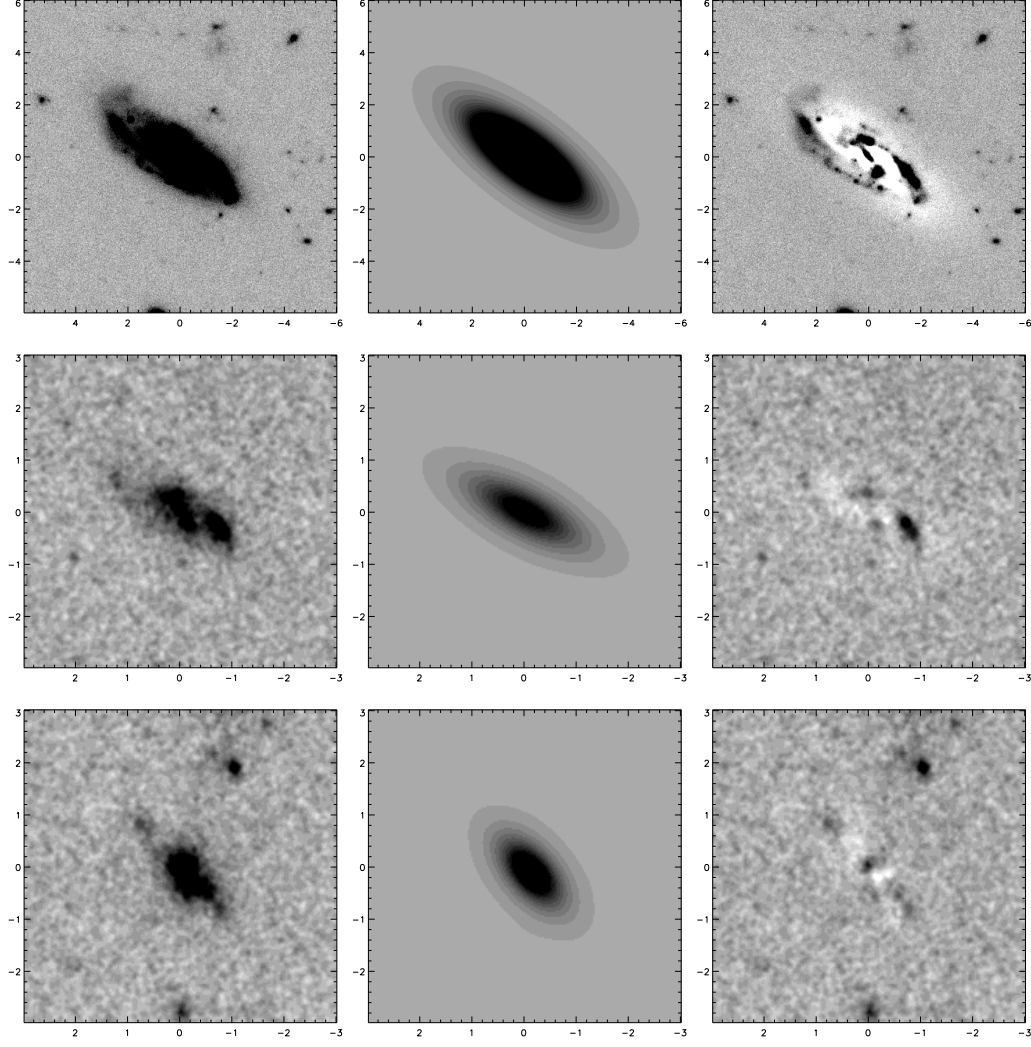


Figure 3. An investigation into the rest-frame optical morphology of the  $z = 3$  sub-millimetre galaxy in the HUDF, via two-dimensional modelling and comparison with a  $z = 0.345$  spiral galaxy extracted from within the HUDF ACS optical imaging. The top row of  $12 \times 12$  arcsec panels shows, from left to right, the  $V$ -band image of the  $z = 0.345$  spiral, the best-fitting model, and the residual model-subtracted image (the best-fitting model is a disc galaxy with half-light radius  $r_{0.5} = 8$  kpc). The central row shows the effect of moving this galaxy to  $z = 3$ , as then imaged in the  $H_{160}$ -band with WFC3/IR. Again the modelling reclaims the correct physical scalelength, but now the residual image looks like a single “clump”. The bottom row shows analogous plots for the actual HUDF sub-millimetre galaxy. The best-fitting model is a disc galaxy (Sérsic index  $n = 1.09$ ) with a half-light radius of  $r_{0.5} = 4$  kpc).



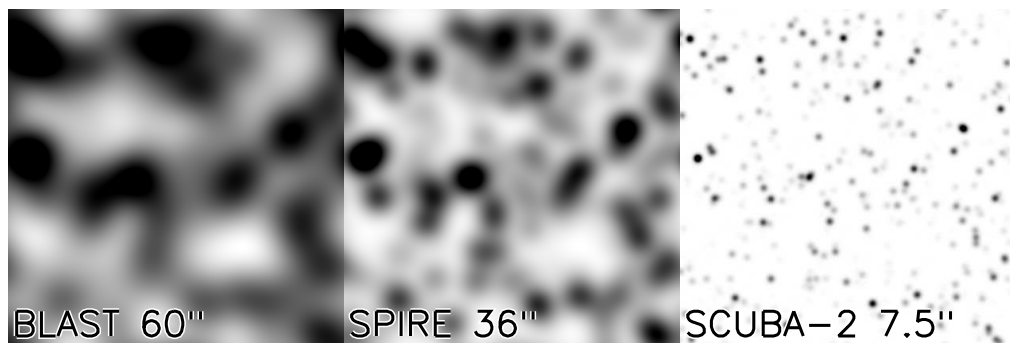


Figure 4. A comparison of BLAST  $500\mu\text{m}$ , *Herschel* SPIRE  $500\mu\text{m}$  and (predicted) SCUBA2  $450\mu\text{m}$  images of a  $50\text{-arcmin}^2$  region of sky, demonstrating the potential power of SCUBA2. A realisation drawn from BLAST  $500\mu\text{m}$  source counts (extracted via P(D) analysis by Patanchon et al. 2009) has been used to create the three  $50\text{ arcmin}^2$  simulated images shown in the grey-scale panels, where the source population has been convolved with the appropriate beam sizes for BLAST, *Herschel*+SPIRE and JCMT+SCUBA2 as indicated in each panel (Devlin et al. 2009; Griffin et al. 2010; Holland et al. 2006). The synthesized SCUBA2 image on the right contains  $\approx 30$  sources with  $S_{450} > 10\text{ mJy}$ .

simply a result of one of the brightest knots in the spiral arms coming to dominate the residual image after convolution with the WFC3/IR  $H_{160}$  point-spread function.

This experiment at least illustrates that one should be cautious in interpreting apparent secondary clumps in the near-infrared images of high-redshift sub-millimetre galaxies as evidence for interactions/mergers fueling or triggering the extreme star-formation activity. In fact, as can be seen from the final panel in Figure 3, the actual sub-millimetre galaxy displays little obvious sign of a significant secondary component after subtraction of the best-fitting axi-symmetric disc-galaxy model. The high star-formation rate in this galaxy could of course be merger-driven but, if so, then there is little obvious evidence of such an event in this, the very best available *HST* near-infrared imaging.

## 6. Conclusion - the nature of sub-millimetre galaxies

From the available evidence I conclude that the archetypal “8-mJy” sub-millimetre galaxy **i)** lies at  $z = 2 - 3$ , **ii)** is forming stars at  $\approx 700\text{ M}_\odot\text{ yr}^{-1}$ , **iii)** has a stellar mass of  $M_* \approx 2 - 3 \times 10^{11}\text{ M}_\odot$ , **iv)** has a molecular gas mass of  $M_{\text{gas}} \approx 0.5 - 2 \times 10^{11}\text{ M}_\odot$ , **v)** has a dynamical mass of  $M_{\text{dyn}} \approx 3 - 5 \times 10^{11}\text{ M}_\odot$ , **vi)** has an implied dark matter halo mass of  $M_h \sim 5 \times 10^{12}\text{ M}_\odot$ , **vii)** is a fairly mature (possibly interacting) star-forming disc galaxy with  $r_{0.5} \approx 3\text{ kpc}$ , and **viii)** has a SSFR  $\approx 2 - 3\text{ Gyr}^{-1}$ , as “expected” for a normal star-forming galaxy at these redshifts (Daddi et al. 2007; Kajisawa et al. 2010; see also the value of SSFR =  $2.2\text{ Gyr}^{-1}$  for sub-millimetre galaxies at  $z \approx 2.3$  reported by Ricciardelli et al. 2010).

Over the next 3 years it will be possible to explore the rest-frame optical morphologies of significant samples of sub-millimetre galaxies as a result of large-scale *HST* WFC3/IR imaging programmes, such as the CANDELS survey (Grogin et al. 2011). In addition, the deep far-infrared imaging provided by the *Herschel* SPIRE+PACS imag-

ing programmes (e.g. HerMES; Oliver et al. 2010) has the capability to provide vastly improved constraints on dust temperatures, far-infrared luminosities, and hence inferred star-formation rates. However, there can be little doubt that the main obstacle to obtaining a clean and comprehensive view of the sub-millimetre galaxy population remains the lack of unconfused sub-millimetre imaging over significant areas of sky. This is especially true at the highest redshifts, where radio identifications become extremely challenging even with the EVLA, and where *Herschel* detections can become confined to the  $500\mu\text{m}$  band where the angular resolution delivered is no better than that delivered by BLAST at  $250\mu\text{m}$  (see Figure 1). As has long been known, what is still really required to unlock the power of both the *Herschel* imaging, and the other key *Spitzer* and *HST* survey programmes, is deep  $450\mu\text{m}$  imaging with SCUBA2 which, mounted on the 15-m JCMT, will deliver imaging over degree-scale areas with a beam-size of  $\approx 7.5$  arcsec (FWHM). The power of such imaging over that provided by BLAST or *Herschel* in their longest wavelength channels is illustrated in Figure 4. Armed with such data, we can genuinely aspire to a proper understanding of the role of the sub-millimetre galaxy population in the overall story of galaxy formation and evolution.

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